Materials for Quantum Leap: Select Examples

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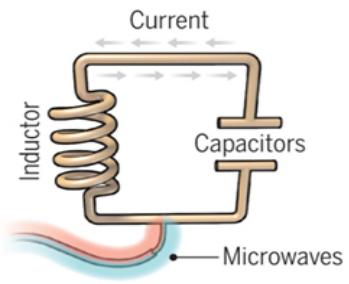
August 14, 2018

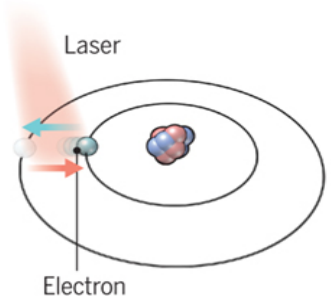
MPS Advisory Committee Meeting

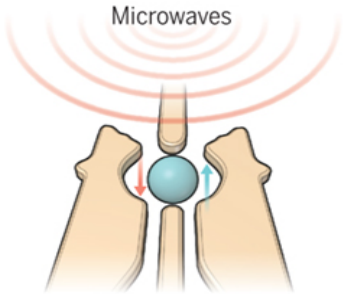
Materials and Platforms for Quantum Leap

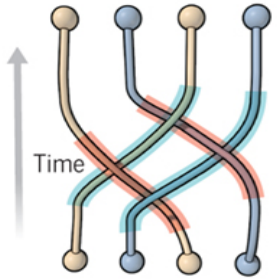
A bit of the action

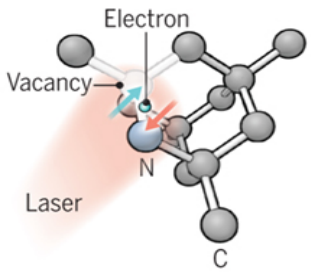
In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.









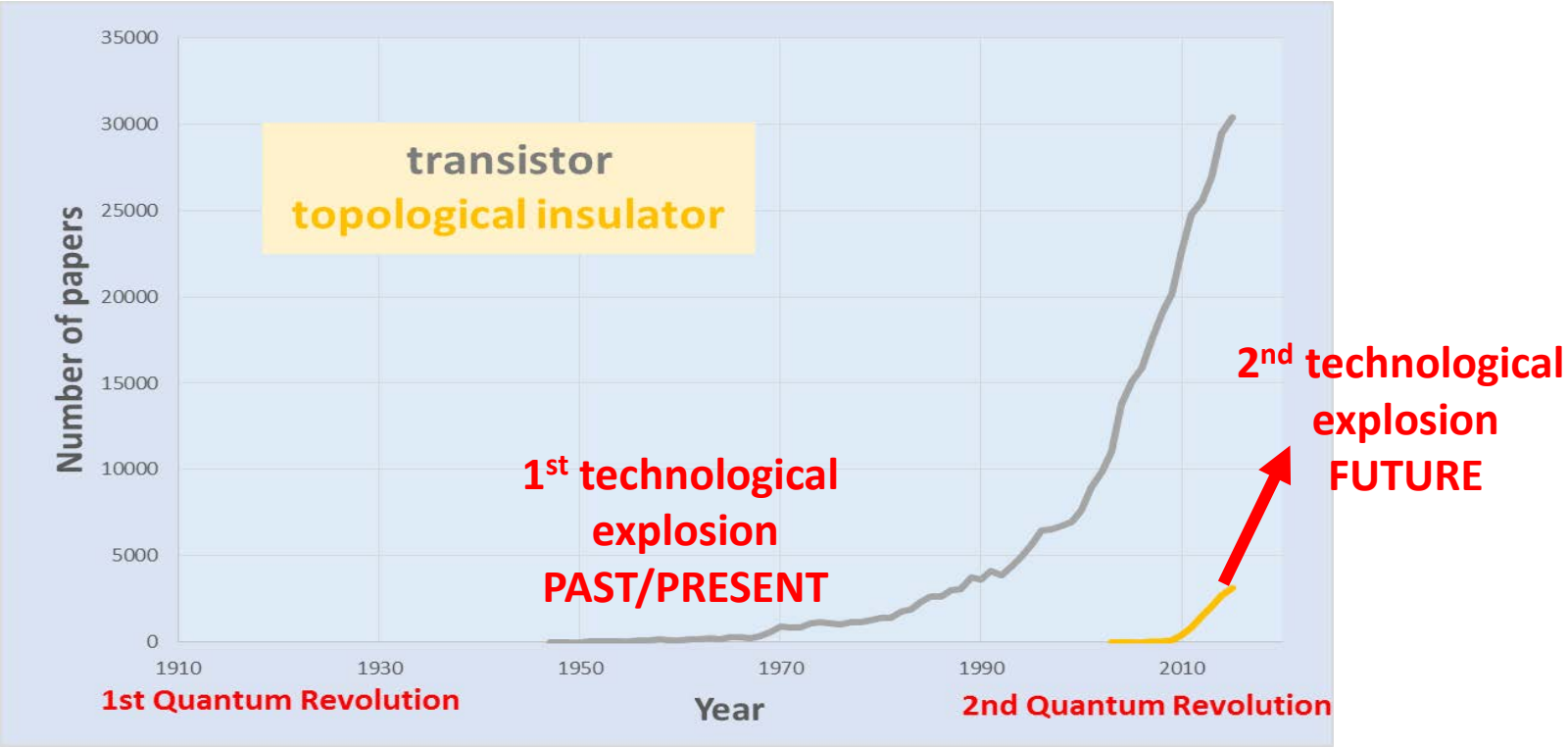


	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures.Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

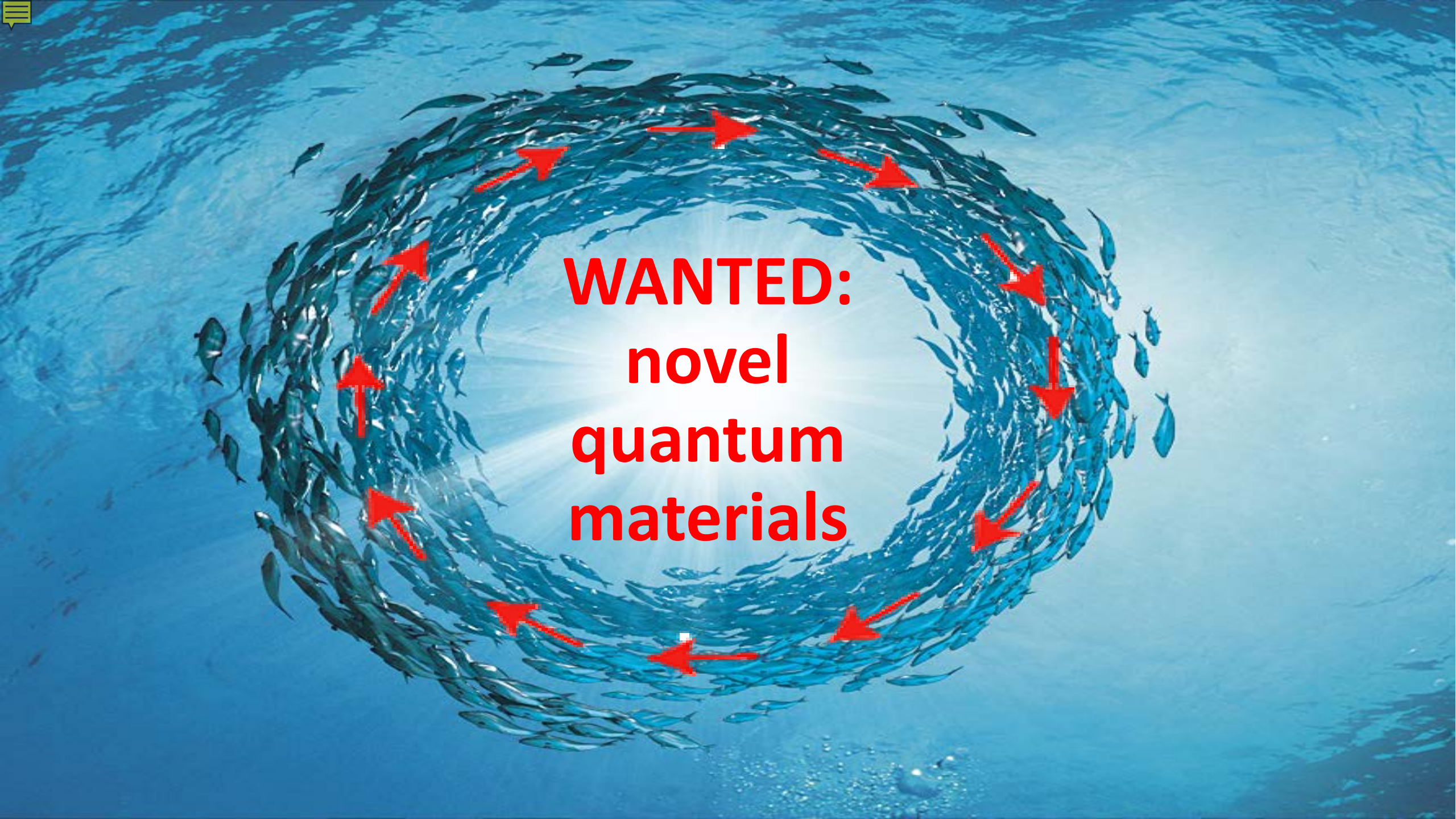
Science, 354 (2016) 1090

Timeline



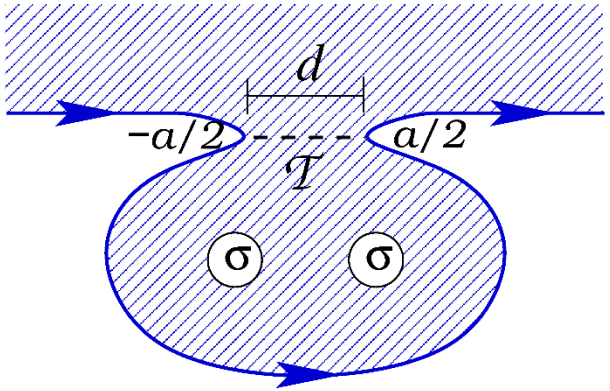
Quantum mechanics 1905-1930 → Band theory 1928 → Transistor 1947 → Progress of integration → Limits of integration (Moore's law) → 

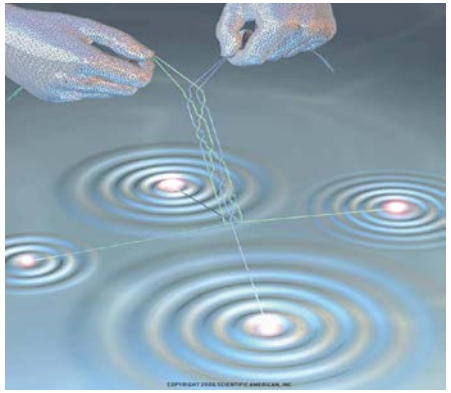
Early topology concepts XVII – XIX centuries → Prediction of topological phases 80' → time-reversal symmetry protected edge states 1987-88 → beyond Moore's law → 

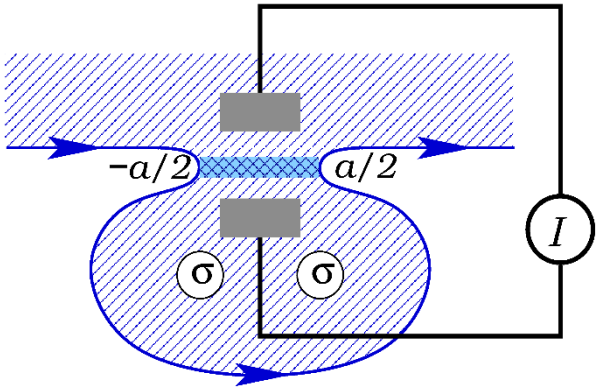

WANTED:
novel
quantum
materials

It starts with theory

Implementing Phase Gates with Ising Anyons, Kirill Shtengel, UC-Riverside; **DMR 0748925**







What: Braiding (center image) is an operation used to manipulate information encoded in anyons. This work proposes models of using a current of anyons AROUND other anyons. Left: a design of a system controlled by simple gate voltage; right: a solution with control achieved by current bias.

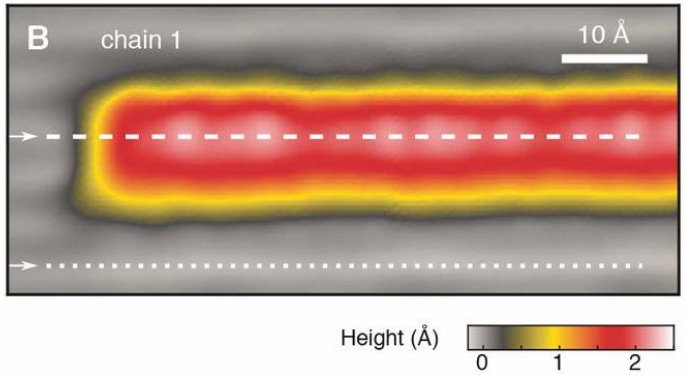
Why do we care: Beyond Majoranas, there are many types of so called non-Abelian anyons. But how to use them in practice? This work offers solutions that can be tested experimentally in real materials.

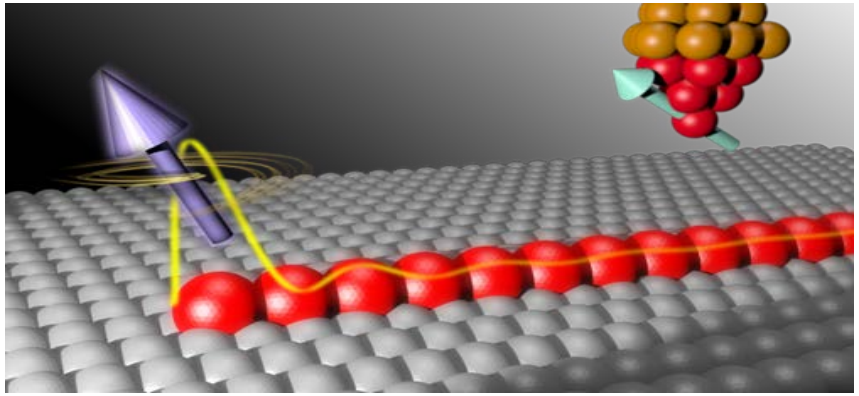
Impact: The future of quantum computing depends on our ability to find materials – hosts of stable, long- lived and accessible qubits.

PRL 104, 180505 (2010); PRB 82, 180519(R) (2010), Editors' Suggestion

Towards stable qubits

Majorana Spin Litmus Test; Ali Yazdani, Princeton University; **DMR 1608848 and DMR 1420541**





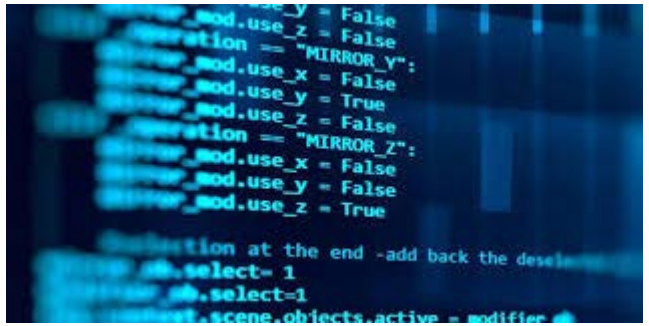
What: Chain of magnetic iron atoms on lead hosts elusive Majorana quasiparticles. Left: topography of a chain, right: schematic of the spin-polarized scanning tunneling microscope measurement.

Why do we care: Search for Majorana particles was on for many decades; the elusive particle that is its own anti-particle is in the center of interest of high energy physics, and more recently also materials sciences. This experiment provides the first-ever “smoking gun” hard evidence for Majorana quasiparticle from measuring spin.

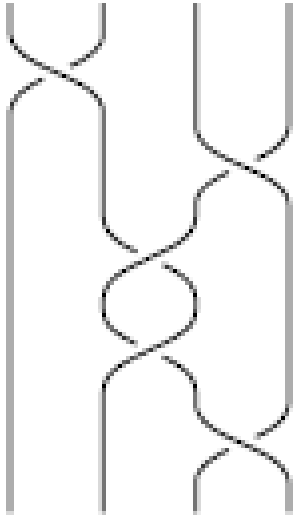
Impact: We have no stable qubits! Majoranas provide a quantum state which is protected from decoherence, and ideal for a stable quantum qubit.

Science, 10.1126, 3670 (2017)

Convergence: materials + algorithms + devices

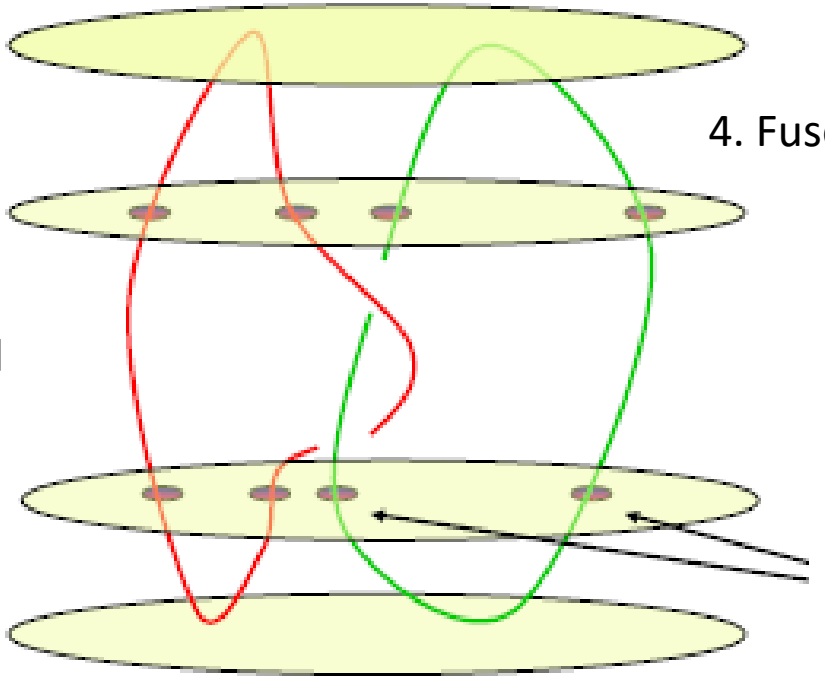


CISE
readout, software



DMS
braiding, algorithms

5. Readout

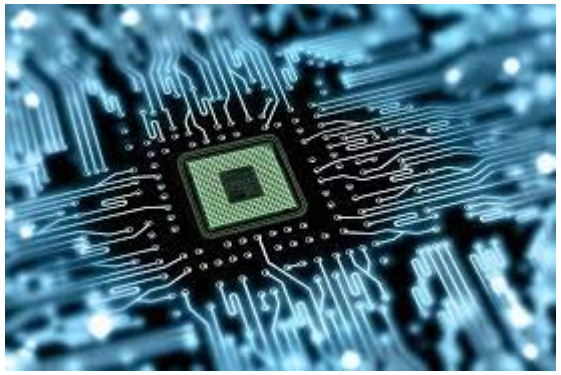


4. Fuse

3. Braid

2. Create anyons

1. Initialize

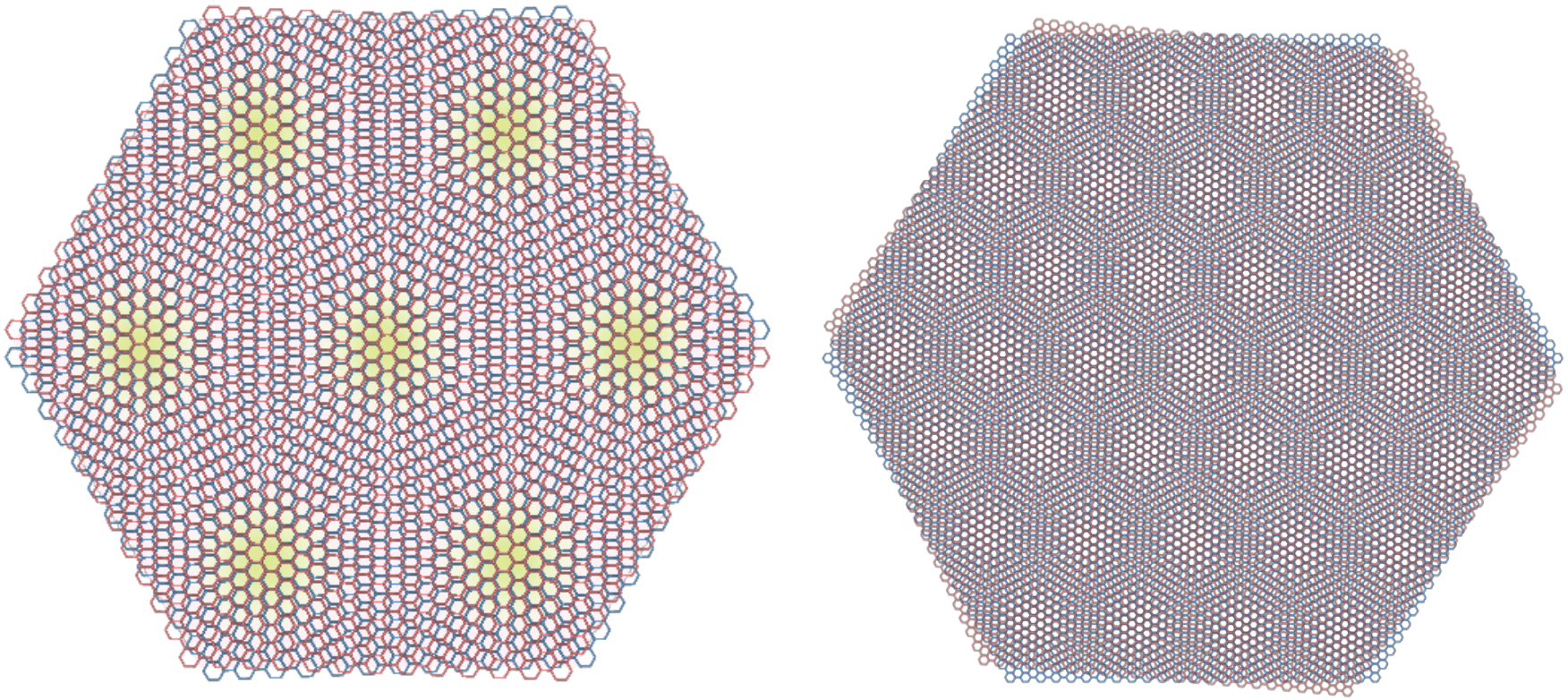


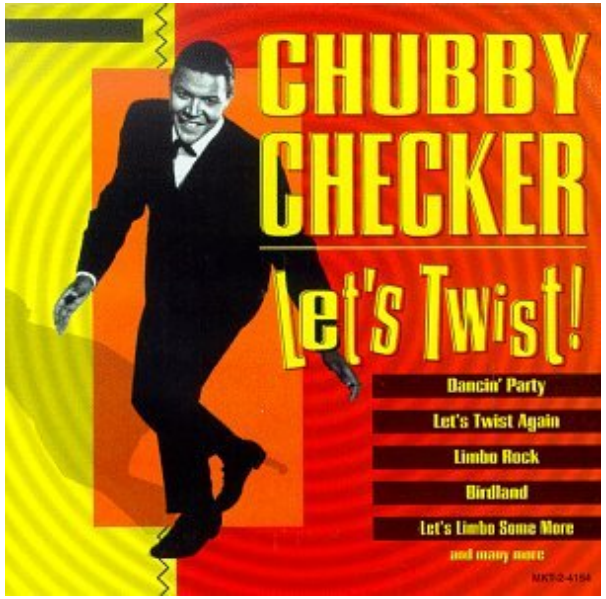
ENG
device, control

DMR
materials platform

Goal: Topological Quantum Computing

New approaches: Twistronics





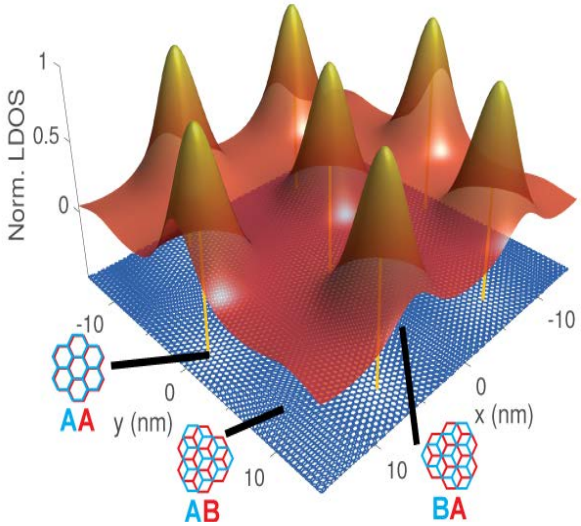


Fig. 1 Twisted bilayer graphene - At half filling, electrons sit on the density of states peaks at the AA overlap points in the Moiré pattern [Cao *et al.* Nature (2018a)].

Nature 556, 80 (2018) and Nature 556, 43 (2018)

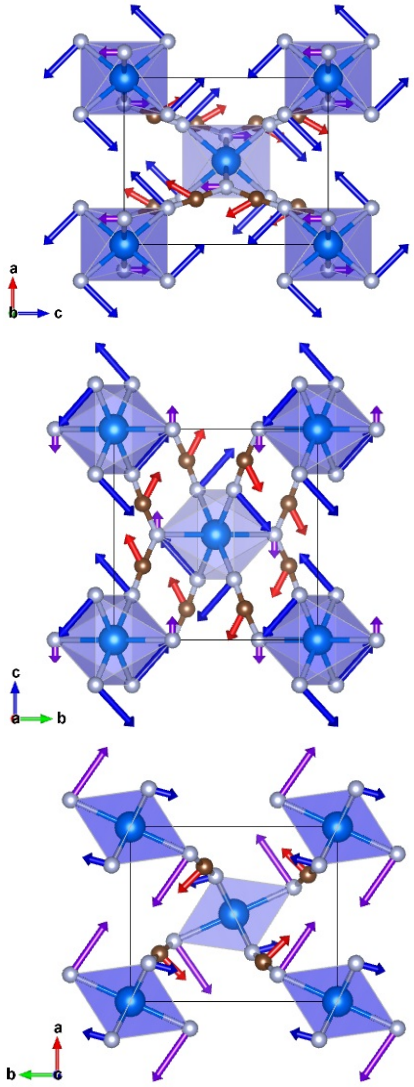
DMR-1405221, DMR-1231319, DMR-0819762, ECS-0335765

Old approaches: from semiclassical to quantum

- Competing magnetostructural phases in a semiclassical system sport a rich *P* – *T* – *B* phase diagram
- high pressure vibrational properties work + lattice dynamics calculations to reveal how + why structural distortions trigger magnetic transitions
- sequence of soft rotational modes are driving force → evidence for strong spin-lattice interactions
- predictions for new high pressure magnetic phase: unique reorientation of exchange planes
- many quantum phases supported by cooperative distortions → Mn(II) ion revealed as a surprising building block for “quantum” materials

Nature Quant. Mater. **2**, 65 (2017)

DMR-1707846



$Mn[N(CN)_2]_2$

Avery Blockmon, U of Tennessee

Supported by: MPS Alliances for Graduate Education and the Professoriate – Graduate Research Supplements (AGEP-GRS)

Program development

Dear Colleague Letter NSF 17-053

Funding Opportunity – A "Quantum Leap" Demonstration of Topological Quantum Computing Funded by CMP, CMMT and EPM programs

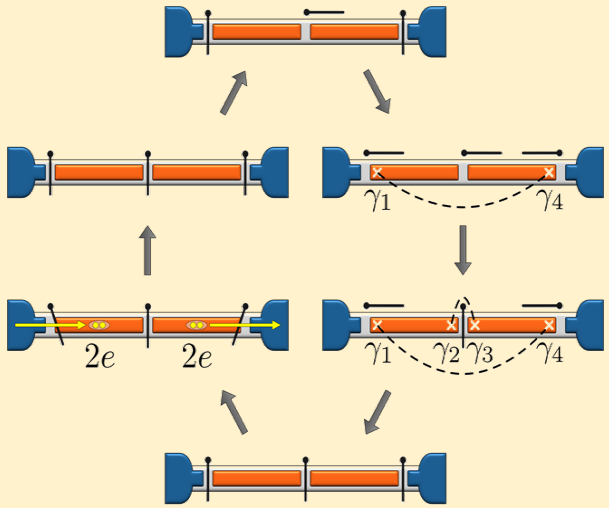
Goal: To challenge researchers to propose transformative research leading to the successful experimental demonstration of a topological qubit based on braiding anyon world lines or other known or creative new mechanisms enabling viable topological quantum computing.

Mode: whitepaper leading to EAGER proposal

Level of support: up to 300k$ over 2 years

Key contacts:
CMP: Tomasz Durakiewicz, tdurakie@nsf.gov
CMMT: Daryl Hess, dhess@nsf.gov
EPM: Miriam Deutsch, mdeutsch@nsf.gov

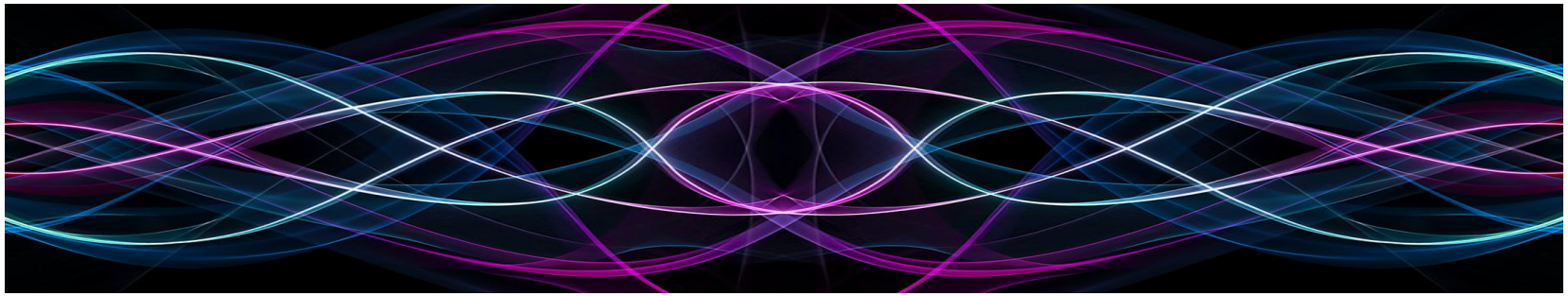
Announced: Feb 6, 2017



Example of proposed experiment to demonstrate manipulation of Majoranas
D. Aasen et al., Phys. Rev. X 6, 031016 (2016)
Sets of semiconducting wires coated with a superconducting island and bulk superconductor that are bridged by a gate-tunable "valves."

EAGER:BRAIDING projects, 2 yr/$300k

- **Parity control and braiding of Majorana fermions in S-TI-S Josephson junction networks**:1745304; Smitha Vishveshwara; Dale Van Harlingen; University of Illinois at Urbana-Champaign
- **Majorana Bound States in Semiconductor Nanowire Networks**, Award Number:1743972;Sergey Frolov; University of Pittsburgh
- **Collaborative Research: Manipulation of Majorana Modes in Topological Crystalline Insulator Nanowires:**1743896 and 1743913; Judy Cha; Yale University and James Williams; University of Maryland College Park
- **Braiding Majorana bound states in atomic chains on a superconducting island**: 1744011; Stevan Nadj-Perge; California Institute of Technology
- **Braiding of Majorana Zero Modes in the Quantum Hall - Superconductor Hybrids:1743907** Finkelstein; Duke University
- **Materials to enable voltage-gateable Majorana systems in silicon using top-down fabrication techniques:1743986 ;** Alex Levchenko, Maxim Vavilov, Robert McDermott, Susan Coppersmith, Mark Eriksson; University of Wisconsin-Madison
- **2nd round 2018 : 8 proposals**



Q-AMASE-i

Announced: Aug 2, 2018
(NSF 18-578) Enabling Quantum Leap: Convergent Accelerated Discovery Foundries for Quantum Materials Science, Engineering and Information (Q-AMASE-i)- DMR + DMS + ECCS +OAC/CISE
https://www.nsf.gov/pubs/2018/nsf18578/nsf18578.htm

The program will support between 1 and 5 Foundries, depending on available budget.
Anticipated funding level is between $20,000,000.- to $25,000,000.- per Foundry over a six-year period.

Letter of Intent due date is September 17, 2018, and Full Proposal deadline is November 05, 2018.

Q-AMASE-I webinar, scheduled for Wednesday, August 15, 2018, at 3PM EST: https://bluejeans.com/611454107